Chapter 5
GPS Absolute Positioning Determination Concepts, Errors, and Accuracies

5-1. General

NAVSTAR GPS determination of a point position on the earth actually uses techniques common to conventional surveying trilateration: an electronic distance measurement resection. The user's receiver simply measures the distance (i.e., ranges) between the earth and the NAVSTAR GPS satellite(s). The user's position is determined by the resected intersection of the observed ranges to the satellites. Each satellite range creates a sphere which forms a circle (approximately) upon intersection with the earth's surface. Given observed ranges to two different satellites, two intersecting circles result from which a horizontal (2D) position on the earth can be computed. Adding a third satellite range creates three spheres, the intersection point of which will provide the X-Y-Z geocentric coordinates of a point. Adding more satellite ranges will provide redundancy in the positioning, which allows adjustment. In actual practice, at least four satellite observations are required in order to resolve timing variations for a 3D position.

5-2. Absolute Positioning

Absolute positioning involves the use of only a single passive receiver at one station location to collect data from multiple satellites in order to determine the station's location. It is not sufficiently accurate for precise surveying or hydrographic positioning uses. It is, however, the most widely used military and commercial GPS positioning method for real-time navigation and location (see paragraph 2-1*b*).

a. The accuracies obtained by GPS absolute positioning are dependent on the user's authorization. The SPS user can obtain real-time point positional accuracies of 100 m. The lower level of accuracies achievable using SPS is due to intentional degradation of the GPS signal by the DoD (S/A). The PPS user (usually a DoD-approved user) can use a decryption device to achieve a point positional (3D) accuracy in the range of 10-16 m with a single-frequency receiver. Accuracies to less than a meter can be obtained from absolute GPS measurements when special equipment and post-processing techniques are employed.

b. Absolute point positioning with the carrier phase. By using broadcast ephemerides, the user is able to use pseudo-range values in real time to determine absolute point positions with an accuracy of between 3 m in the best of conditions and 80 m in the worst. By using a post-processed ephemerides (i.e., precise), the user can expect absolute point positions with an accuracy of near 1 m in the best of conditions and 40 m in the worst.

5-3. Pseudo-Ranging

When a GPS user performs a GPS navigation solution, only an approximate range, or pseudo-range, to selected satellites is measured. In order for the GPS user to determine his/her precise location, the known range to the satellite and the position of those satellites must be known. By pseudo-ranging, the GPS user measures an approximate distance between the antenna and the satellite by correlation of a satellite-transmitted code and a reference code created by the receiver, without any corrections for errors in synchronization between the clock of the transmitter and that of the receiver. The distance the signal has traveled is equal to the velocity of the transmission of the satellite multiplied by the elapsed time of transmission, with satellite signal velocity changes due to tropospheric and ionospheric conditions being considered. Refer to Figure 5-1 for an illustration of the pseudo-ranging concept. (See also paragraph 2-4*a*,*b*.)

a. The accuracy of the positioned point is a function of the range measurement accuracy and the geometry of the satellites, as reduced to spherical intersections with the earth's surface. A description of the geometrical magnification of uncertainty in a GPS-determined point position is Dilution of Precision (DOP), which is discussed in section 5-6*d*(2). Repeated and redundant range observations will generally improve range accuracy. However, the dilution of precision remains the same. In a static mode (meaning the GPS antenna stays stationary), range measurements to each satellite may be continuously remeasured over varying orbital locations of the satellite(s). The varying satellite orbits cause varying positional intersection geometry. In addition, simultaneous range observations to numerous satellites can be adjusted using weighting techniques based on the elevation and pseudo-range measurement reliability.

b. Four pseudo-range observations are needed to resolve a GPS 3D position. (Only three pseudo-range observations are needed for a 2D location.) In practice there are often more than four. This is due to the need to

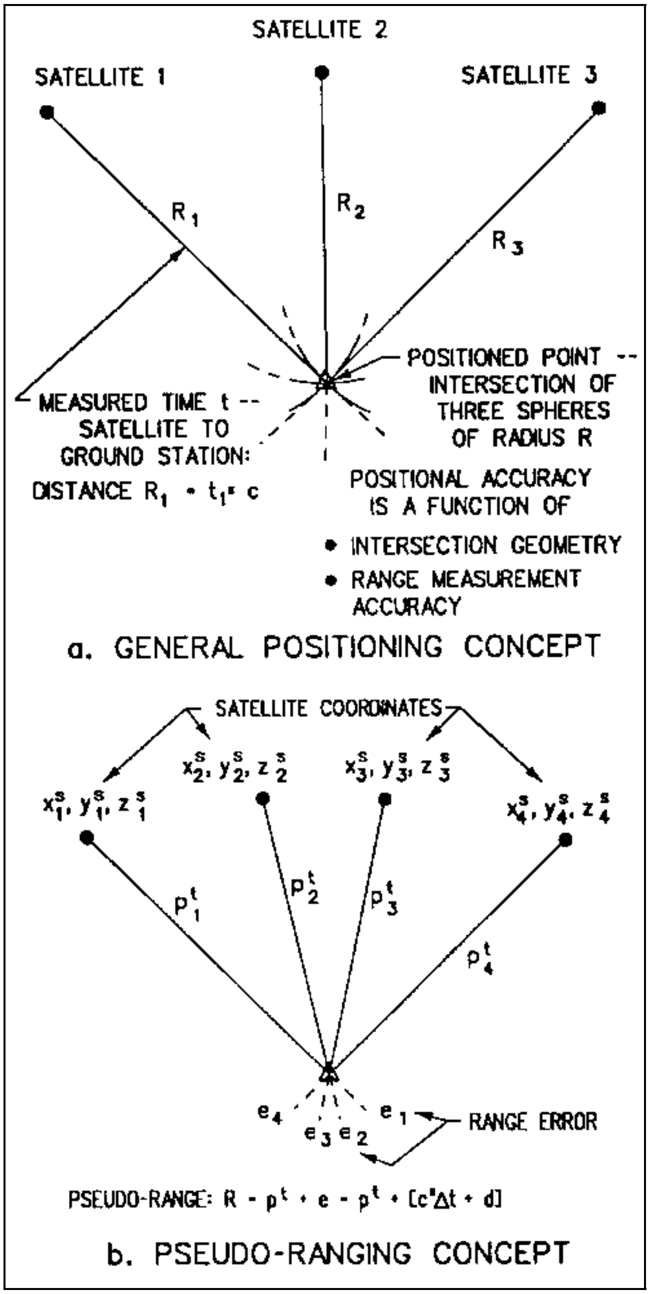

Figure 5-1. GPS satellite range measurement

resolve the clock biases Δt contained in both the satellite and ground-based receiver. Thus, in solving for the X-Y-Z coordinates of a point, a fourth unknown (i.e., clock bias) must also be included in the solution. The solution of the 3D position of a point is simply the solution of four pseudo-range observation equations containing four unknowns, i.e., X, Y, Z, and Δt.

c. A pseudo-range observation is equal to the true range from the satellite to the user ρ^t plus delays due to satellite/receiver clock biases and other effects, as was shown in Figure 5-1.

$$R = p^{t} + c(\Delta t) + d \tag{5-1}$$

where

R = observed pseudo-range

ρ^t = true range to satellite (unknown)

c = velocity of propagation

Δt = clock biases (receiver and satellite)

d = propagation delays due to atmospheric conditions

These are usually estimated from models.

The true range ρ^t is equal to the 3D coordinate difference between the satellite and user.

$$\rho^t = \left[(X^s - X^u)^2 + (Y^s - Y^u)^2 + (Z^s - Z^u)^2\right]^{\frac{1}{2}} \tag{5-2}$$

where

X^s, Y^s, Z^s = known satellite coordinates from ephemeris data

X^u, Y^u, Z^u = unknown coordinates of user which are to be determined.

When four pseudo-ranges are observed, four equations are formed from Equations 5-1 and 5-2.

$$(R_1 - c\ \Delta t - d_1)^2 = \left(X_1^s - X^u\right)^2 + \left(Y_1^s - Y^u\right)^2 + \left(Z_1^s - Z^u\right)^2 \tag{5-3}$$

$$(R_2 - c\ \Delta t - d_2)^2 = \left(X_2^s - X^u\right)^2 + \left(Y_2^s - Y^u\right)^2 + \left(Z_2^s - Z^u\right)^2 \tag{5-4}$$

$$(R_3 - c\ \Delta t - d_3)^2 = \left(X_3^s - X^u\right)^2 + \left(Y_3^s - Y^u\right)^2 + \left(Z_3^s - Z^u\right)^2 \tag{5-5}$$

$$(R_4 - c\ \Delta t - d_4)^2 = \left(X_4^s - X^u\right)^2 + \left(Y_4^s - Y^u\right)^2 + \left(Z_4^s - Z^u\right)^2 \tag{5-6}$$

In these equations, the only unknowns are X^u, Y^u, Z^u, and Δt. Solving these equations at each GPS update yields the user's 3D position coordinates. Adding more pseudo-range observations provides redundancy to the solution. For instance, if seven satellites are simultaneously observed, seven equations are derived, and still only four unknowns result.

d. This solution is highly dependent on the accuracy of the known coordinates of each satellite (i.e., X^s, Y^s, and Z^s), the accuracy with which the atmospheric delays d can be estimated through modeling, and the accuracy of the resolution of the actual time measurement process performed in a GPS receiver (clock synchronization, signal processing, signal noise, etc.). As with any measurement process, repeated and long-term observations from a single point will enhance the overall positional reliability.

5-4. GPS Error Sources

There are numerous sources of measurement error that influence GPS performance. The sum of all systematic errors or biases contributing to the measurement error is referred to as range bias. The observed GPS range, without removal of biases, is referred to as a biased range or "pseudo-range." Principal contributors to the final range error that also contribute to overall GPS error are ephemeries error, satellite clock and electronics inaccuracies, tropospheric and ionospheric refraction, atmospheric absorption, receiver noise, and multipath effects. Other errors include those induced by DoD (Selective Availability (S/A) and Anti-Spoofing (A/S)). In addition to these major errors, GPS also contains random observation errors, such as unexplainable and unpredictable time variation. These errors are impossible to model and correct. The following paragraphs discuss errors associated with absolute GPS positioning modes. Many of these errors are either eliminated or significantly minimized when GPS is used in a differential mode. This is due to the same errors being common to both receivers during simultaneous observing sessions. For a more detailed analysis of these errors, consult one of the technical references listed in Appendix A.

a. *Ephemeris errors and orbit perturbations.* Satellite ephemeris errors are errors in the prediction of a satellite position which may then be transmitted to the user in the satellite data message. Ephemeris errors are satellite dependent and very difficult to completely correct and compensate for because the many forces acting on the predicted orbit of a satellite are difficult to measure directly. Because direct measurement of all forces acting on a satellite orbit is difficult, it is nearly impossible to accurately account or compensate for those error sources when modeling the orbit of a satellite. The previous accuracy levels stated are subject to performance of equipment and conditions. Ephemeris errors produce equal error shifts in calculated absolute point positions.

b. *Clock stability.* GPS relies very heavily on accurate time measurements. GPS satellites carry rubidium and cesium time standards that are usually accurate to 1 part in 10^{12} and 1 part in 10^{13}, respectively, while most receiver clocks are actuated by a quartz standard accurate to 1 part in 10^8. A time offset is the difference between the time as recorded by the satellite clock and that recorded by the receiver. Range error observed by the user as the result of time offsets between the satellite and receiver clock is a linear relationship and can be approximated by the following equation:

$$R_E = T_O * c \tag{5-7}$$

where

R_E = user equivalent range error

T_O = time offset

c = speed of light

(1) The following example shows the calculation of the user equivalent range error (UERE or UR).

T_O = 1 microsecond (µs) = 10^{-06} seconds (s)

c = 299,792,458 m/s

From Equation 5-7:

R_E = (10^{-06} seconds) * 299,792,458 m/s

= 299.79 m = 300 m user equivalent range error

(2) In general, unpredictable transient situations that produce high-order departures in clock time can be

ignored over short periods of time. Even though this may be the case, predictable time drift of the satellite clocks is closely monitored by the ground control stations. Through closely monitoring the time drift, the ground control stations are able to determine second-order polynomials which accurately model the time drift. The second-order polynomial determined by the ground control station to model the time drift is included in the broadcast message in an effort to keep this drift to within 1 millisecond (ms). The time synchronization between the GPS satellite clocks is kept to within 20 nsec (ns) through the broadcast clock corrections as determined by the ground control stations and the synchronization of GPS standard time to the Universal Time Coordinated (UTC) to within 100 ns. Random time drifts are unpredictable, thereby making them impossible to model.

(3) GPS receiver clock errors can be modeled in a manner similar to GPS satellite clock errors. In addition to modeling the satellite clock errors and in an effort to remove them, an additional satellite should be observed during operation to simply solve for an extra clock offset parameter along with the required coordinate parameters. This procedure is based on the assumption that the clock bias is independent at each measurement epoch. Rigorous estimation of the clock terms is more important for point positioning than for differential positioning. Many of the clock terms cancel when the position equations are formed from the observations during a differential survey session.

c. Ionospheric delays. GPS signals are electromagnetic signals and as such are nonlinearly dispersed and refracted when transmitted through a highly charged environment like the ionosphere. Dispersion and refraction of the GPS signal is referred to as an ionospheric range effect because dispersion and refraction of the signal result in an error in the GPS range value. Ionospheric range effects are frequency dependent.

(1) The error effect of ionosphere refraction on the GPS range values is dependent on sunspot activity, time of day, and satellite geometry. GPS operations conducted during periods of high sunspot activity or with satellites near the horizon produce range results with the most error. GPS operations conducted during periods of low sunspot activity, during the night, or with a satellite near the zenith produce range results with the least amount of ionospheric error.

(2) Resolution of ionospheric refraction can be accomplished by use of a dual-frequency receiver (a receiver that can simultaneously record both L1 and L2 frequency measurements). During a period of uninterrupted observation of the L1 and L2 signals, these signals can be continuously counted and differenced. The resultant difference reflects the variable effects of the ionosphere delay on the GPS signal. Single-frequency receivers used in an absolute and differential positioning mode typically rely on ionospheric models that model the effects of the ionosphere. Recent efforts have shown that significant ionospheric delay removal can be achieved using signal frequency receivers.

d. Tropospheric delays. GPS signals in the L-band level are not dispersed by the troposphere, but they are refracted. The tropospheric conditions causing refraction of the GPS signal can be modeled by measuring the dry and wet components. The dry component is best approximated by the following equation:

$$D_C = (2.27 * 0.001) * P_O \tag{5-8}$$

where

D_C = dry term range contribution in zenith direction in meters

P_O = surface pressure in millibar

(1) The following example shows the calculation of average atmospheric pressure P_O = 765 mb:

From Equation 5-8:

D_C = (2.27 * 0.001) * 765 mb

= 1.73655 m = 1.7 m, the dry term range error contribution in the zenith direction

(2) The wet component is considerably more difficult to approximate because its approximation is dependent not just on surface conditions, but also on the atmospheric conditions (water vapor content, temperature, altitude, and angle of the signal path above the horizon) along the entire GPS signal path. As this is the case, there has not been a well-correlated model that approximates the wet component.

e. Multipath. Multipath describes an error affecting positioning that occurs when the signal arrives at the receiver from more than one path. Multipath normally occurs near large reflective surfaces, such as a metal building or structure. GPS signals received as a result of multipath give inaccurate GPS positions when processed. With the newer receiver and antenna designs and sound prior mission planning to eliminate possible causes of multipath, the effects of multipath as an error source can be minimized. Averaging of GPS signals over a period of time can also reduce the effects of multipath.

f. Receiver noise. Receiver noise includes a variety of errors associated with the ability of the GPS receiver to measure a finite time difference. These include signal processing, clock/signal synchronization and correlation methods, receiver resolution, signal noise, and others.

g. Selective Availability (S/A) and Anti-Spoofing (A/S). S/A purposely degrades the satellite signal to create position errors. This is done by dithering the satellite clock and offsetting the satellite orbits. The effects of S/A can be eliminated by using differential techniques discussed further in Chapter 6. A-S is implemented by interchanging the P-code with a classified Y-code. This denies users who do not possess an authorized decryption device. Manufacturers of civil GPS equipment have developed methods such as squaring or cross correlation in order to make use of the P-code when it is encrypted.

5-5. User Equivalent Range Error

The previous sources of errors or biases are principal contributors to overall GPS range error. This total error budget is often summarized as the UERE. As mentioned previously, they can be removed or at least effectively suppressed by developing models of their functional relationships in terms of various parameters that can be used as a corrective supplement for the basic GPS information. Differential techniques also eliminate many of these errors. Table 5-1 lists the more significant sources for errors and biases and correlates them to the segment source.

5-6. Absolute GPS Accuracies

The absolute range accuracies obtainable from GPS are largely dependent on which code (C/A or P) is used to determine positions. These range accuracies (i.e., UERE), when coupled with the geometrical relationships of the satellites during the position determination (i.e., DOP), result in a 3D confidence ellipsoid which depicts uncertainties in all three coordinates. Given the changing satellite geometry and other factors, GPS accuracy is time/location dependent. Error propagation techniques are used to define nominal accuracy statistics for a GPS user.

a. Root mean square error measures. Two-dimensional (2D) (horizontal) GPS positional accuracies are normally estimated using a root mean square (RMS) radial error statistic. A 1-σ RMS error equates to the radius of a circle in which the position has a 63 percent probability of falling. A circle of twice this radius (i.e., 2-σ RMS or 2DRMS) represents (approximately) a 97 percent positional probability circle. This 97 percent probability circle, or 2DRMS, is the most common positional accuracy statistic used in GPS surveying. In some instances, a 3DRMS or 99+ percent probability is used. This RMS error statistic is also related to the positional variance-covariance matrix. (Note that an RMS error statistic represents the radius of a circle and therefore is not preceded by a ± sign.)

Table 5-1
GPS Range Measurement Accuracy

Segment Source	Error Source	Absolute Positioning: C/A-code Pseudo-range, m	Absolute Positioning: P-code Pseudo-range, m	Differential Positioning, m (P-code)
Space	Clock stability	3.0	3.0	Negligible
	Orbit perturbations	1.0	1.0	Negligible
	Other	0.5	0.5	Negligible
Control	Ephemeris predictions	4.2	4.2	Negligible
	Other	0.9	0.9	Negligible
User	Ionosphere	3.5	2.3	Negligible
	Troposphere	2.0	2.0	Negligible
	Receiver noise	1.5	1.5	1.5
	Multipath	1.2	1.2	1.2
	Other	0.5	0.5	0.5
1-σ UERE		±12.1	±6.5	±2.0

[a] Without S/A.

b. Probable error measures. 3D GPS accuracy measurements are most commonly expressed by Spherical Error Probable, or SEP. This measure represents the radius of a sphere with a 50 percent confidence or probability level. This spheroid radial measure only approximates the actual 3D ellipsoid representing the uncertainties in the geocentric coordinate system. In 2D horizontal positioning, a Circular Error Probable (CEP) statistic is commonly used, particularly in military targeting. CEP represents the radius of a circle containing a 50 percent probability of position confidence.

c. Accuracy comparisons. It is important that GPS accuracy measures clearly identify the statistic from which they are derived. A "100-m" or "3-m" accuracy statistic is meaningless unless it is identified as being either 1D, 2D, or 3D, along with the applicable probability level. For example, a PPS-16 m 3D accuracy is, by definition, SEP (i.e. 50 percent). This 16-m SEP equates to 28-m 3D 95 percent confidence spheroid, or when transformed to 2D accuracy, roughly 10 m CEP, 12 m RMS, 24 m 2DRMS, and 36 m 3DRMS. See Table 5-2 for further information on GPS measurement statistics. In addition, absolute GPS point positioning accuracies are defined relative to an earth-centered coordinate system/datum. This coordinate system will differ significantly from local project or construction datums. Nominal GPS accuracies may also be published as design or tolerance limits and accuracies achieved can differ significantly from these values.

d. Dilution of Precision (DOP). The final positional accuracy of a point determined using absolute GPS survey techniques is directly related to the geometric strength of the configuration of satellites observed during the survey session. GPS errors resulting from satellite configuration geometry can be expressed in terms of DOP. In mathematical terms, DOP is a scaler quantity used in an expression of a ratio of the positioning accuracy. It is the ratio of the standard deviation of one coordinate to the measurement accuracy. DOP represents the geometrical contribution of a certain scaler factor to the uncertainty (i.e., standard deviation) of a GPS measurement. DOP values are a function of the diagonal elements of the covariance matrices of the adjusted parameters of the observed GPS signal and are used in the point formulations and determinations (Figure 5-2).

(1) General. In a more practical sense, DOP is a scaler quantity of the contribution of the configuration of satellite constellation geometry to the GPS accuracy, in other words, a measure of the "strength" of the geometry of the satellite configuration. In general, the more satellites that can be observed and used in the final solution, the better the solution. Since DOP can be used as a measure of the geometrical strength, it can also be used to selectively choose four satellites in a particular constellation that will provide the best solution.

(2) Geometric dilution of precision (GDOP). The main form of DOP used in absolute GPS positioning is the geometric DOP (GDOP), which is a measure of accuracy in a 3D position and time. The relationship between final positional accuracy, actual range error, and GDOP can be expressed as follows:

$$\sigma_a = \sigma_R * \text{GDOP} \tag{5-9}$$

where

σ_a = final positional accuracy

σ_R = actual range error (UERE)

$$\text{GDOP} = \frac{\left[\sigma_E 2 + \sigma_N 2 + \sigma_u 2 + (c \ . \ \delta_T)^2\right]^{\frac{1}{2}}}{\sigma_R} \tag{5-10}$$

where

σ_E = standard deviation in east value, m

σ_N = standard deviation in north value, m

σ_u = standard deviation in up direction, m

c = speed of light (299,792,458 m/s)

δ_T = standard deviation in time, s

σ_R = overall standard deviation in range, m, usually in the range of 6 m for P-code usage and 12 m for C/A-code usage

(3) Positional dilution of precision (PDOP). PDOP is a measure of the accuracy in 3D position, mathematically defined as:

$$\text{PDOP} = \frac{\left[\sigma_E 2 + \sigma_N 2 + \sigma_U 2\right]^{\frac{1}{2}}}{\sigma_R} \tag{5-11}$$

Table 5-2
Representative GPS Error Measurement Statistics for Absolute Point Positioning

Error Measure Statistic	**Probability %**	**Relative Distance ft(σ)** (1)	**GPS Precise Positioning Service m** (2)		**GPS Standard Positioning Service m** (2)	
Linear Measures			σ_N or σ_E	σ_U	σ_N or σ_E	σ_U
Probable error	50	0.6745 σ	± 4 m	± 9 m	± 24 m	± 53 m
Average error	57.51	0.7979 σ	± 5 m	± 11 m	± 28 m	± 62 m
1-sigma standard error/deviation (3)	68.27	1.00 σ	± 6.3 m	± 13.8 m	± 35.3 m	± 78 m
90% probability (map accuracy standard)	90	1.645 σ	± 10 m	± 23 m	± 58 m	± 128 m
95% probability/confidence	95	1.96 σ	± 12 m	± 27 m	± 69 m	± 153 m
2-sigma standard error/deviation	95.45	2.00 σ	**± 12.6 m**	**± 27.7 m**	**± 70.7 m**	**± 156 m**
99% probability/confidence	99	2.576 σ	± 16 m	± 36 m	± 91 m	± 201 m
3-sigma standard error (near certainty)	99.73	3.00 σ	± 19 m	± 42 m	± 106 m	± 234 m
Two-Dimensional Measures (4)			Circular Radius		Circular Radius	
1-sigma standard error circle (σ_c) (5)	39	1.00 σ_c	6 m		35 m	
Circular error probable (CEP) (6)	50	1.177 σ_c	7 m		42 m	
1-dev root mean square (1DRMS) (3)(7)	63	1.414 σ_c	9 m		50 m	
Circular map accuracy standard	90	2.146 σ_c	13 m		76 m	
95% 2D positional confidence circle	95	2.447 σ_c	15 m		86 m	
2-dev root mean square error (2DRMS) (8)	98^+	2.83 σ_c	**17.8 m**		**100 m**	
99% 2D positional confidence circle	99	3.035 σ_c	19 m		107 m	
3.5-sigma circular near-certainty error	99.78	3.5 σ_c	22 m		123 m	
3-dev root mean square error (3DRMS)	99.9^+	4.24 σ_c	27 m		150 m	
Three-Dimensional Measures			Spherical Radius		Spherical Radius	
1-σ spherical standard error (σ_s) (9)	19.9	1.00 σ_s	9 m		50 m	
Spherical error probable (SEP) (10)	50	1.54 σ_s	13.5 m		76.2 m	
Mean radial spherical error (MRSE) (11)	61	1.73 σ_s	16 m		93 m	
90% spherical accuracy standard	90	2.50 σ_s	22 m		124 m	
95% 3D confidence spheroid	95	2.70 σ_s	24 m		134 m	
99% 3D confidence spheroid	99	3.37 σ_s	30 m		167 m	
Spherical near-certainty error	99.89	4.00 σ_s	35 m		198 m	

Notes:

Most Commonly Used Statistics Shown in Bold Face Type.
Estimates not applicable to differential GPS positioning. Circular/Spherical error radii do not have ± signs.

Absolute positional accuracies are derived from GPS simulated user range errors/deviations and resultant geocentric coordinate (X-Y-Z) solution covariance matrix, as transformed to a local datum (N-E-U or ϕ-λ-h). GPS accuracy will vary with GDOP and other numerous factors at time(s) of observation. The 3D covariance matrix yields an error ellipsoid. Transformed ellipsoidal dimensions given (i.e., σ_N- σ_E- σ_U) are only average values observed under nominal GDOP conditions. Circular (2D) and spherical (3D) radial measures are only approximations to this ellipsoid, as are probability estimates.

(Continued)

Table 5-2
(Concluded)

(1) Valid for 2-D and 3-D only if $\sigma_N = \sigma_E = \sigma_U$. ($\sigma_{min}/\sigma_{max}$) generally must be ≥ 0.2. Relative distance used unless otherwise indicated.
(2) Representative accuracy based on 1990 FRNP simulations for PPS and SPS (FRNP estimates shown in bold), and that $\sigma_N \approx \sigma_E$. SPS may have significant short-term variations from these nominal values.
(3) Statistic used to define USACE hydrographic survey depth and positioning criteria.
(4) 1990 FRNP also proposes SPS maintain, at minimum, a 2D confidence of 300 m @ 99.99% probability.
(5) $\sigma_c \simeq 0.5\ (\sigma_N + \sigma_E)$ -- approximates standard error ellipse.
(6) CEP $\simeq 0.589\ (\sigma_N + \sigma_E) \approx 1.18\ \sigma_c$.
(7) 1DRMS $\simeq (\sigma_N^2 + \sigma_E^2)^{1/2}$.
(8) 2DRMS $\simeq 2\ (\sigma_N^2 + \sigma_E^2)^{1/2}$.
(9) $\sigma_s \simeq 0.333\ (\sigma_N + \sigma_E + \sigma_U)$.
(10) SEP $\simeq 0.513\ (\sigma_N + \sigma_E + \sigma_U)$.
(11) MRSE $\simeq (\sigma_N^2 + \sigma_E^2 + \sigma_U^2)^{1/2}$.

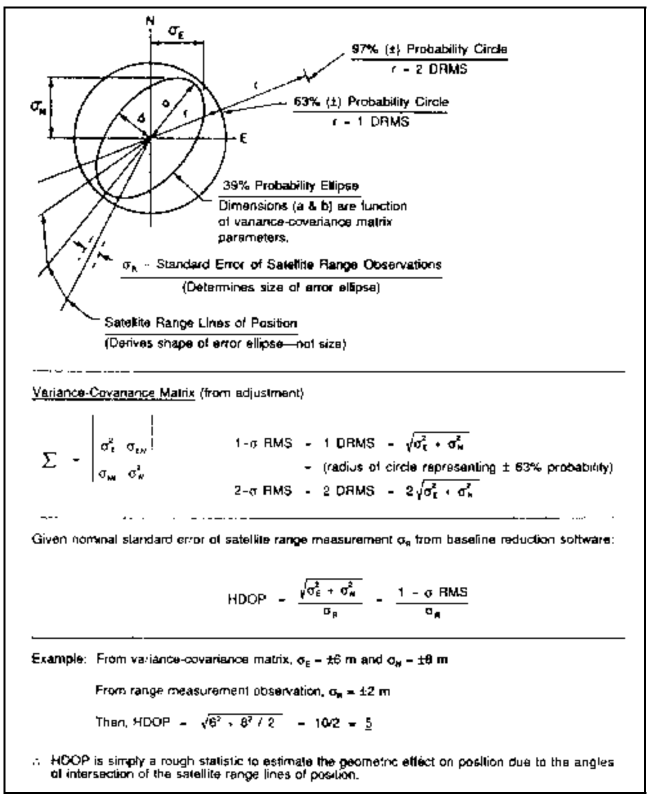

Figure 5-2. Dilution of Precision

where all variables are equivalent to those used in Equation 5-10.

(a) PDOP values are generally developed from satellite ephemerides prior to the conducting of a survey. When developed prior to a survey, PDOP can be used to determine the adequacy of a particular survey schedule. This is valid for rapid static or kinematic but is less valid for long duration static.

(b) The key to understanding PDOP is to remember that it represents position recovery at an instant in time and is not representative of a whole session of time. PDOP error is generally given in units of meters of error per 1-m error in the pseudo-range measurement (i.e., m/m). When using pseudo-range techniques, PDOP values in the range of 4-5 m/m are considered very good, while PDOP values greater than 10 m/m are considered very poor. For static surveys it is generally desirable to obtain GPS observations during a time of rapidly changing GDOP and/or PDOP.

(c) When the values of PDOP or GDOP are viewed over time, peak or high values (>10 m/m) can be associated with satellites in a constellation of poor geometry. The higher the PDOP or GDOP, the poorer the solution for that instant in time. This is critical in determining the acceptability of real-time navigation and photogrammetric solutions. Poor geometry can be the result of satellites being in the same plane, orbiting near each other, or at similar elevations.

(4) Horizontal dilution of precision (HDOP). HDOP is a measurement of the accuracy in 2D horizontal position, mathematically defined as:

$$\text{HDOP} = \frac{\left(\sigma_E 2 + \sigma_N 2\right)^{\frac{1}{2}}}{\sigma_R} \qquad (5\text{-}12)$$

This HDOP statistic is most important in evaluating GPS surveys intended for horizontal control. The HDOP is basically the RMS error determined from the final variance-covariance matrix divided by the standard error of the range measurements. HDOP roughly indicates the effects of satellite range geometry on a resultant position.

(5) Vertical dilution of precision (VDOP). VDOP is a measurement of the accuracy in standard deviation in vertical height, mathematically defined as:

$$VDOP = \frac{\sigma_u}{\sigma_R} \tag{5-13}$$

(6) Acceptable DOP values. Table 5-3 indicates generally accepted DOP values for a baseline solution.

(7) Additional material. Additional material regarding GPS positional accuracy may be found in the references listed in Appendix A.

Table 5-3
Acceptable DOP Values

GDOP and PDOP: Less than 10 m/m -- optimally 4-5 m/m.
In static GPS surveying, it is desirable to have a GDOP/PDOP that changes during the time of GPS survey session.
The lower the GDOP/PDOP, the better the instantaneous point position solution is.
HDOP and VDOP: 2 m/m for the best constellation of four satellites.